HIGH POWER HOLLOW ELECTRODE THYRATRON-TYPE SWITCHES

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Abstract: A review of recent developments in a new group of high power switches, including the pseudo-spark and BLT, is presented. Experiments are reported wherein it is shown that for several key aspects of high power switching the pseudo-spark and BLT switches are superior to either high pressure spark gap switches and/or thyratrons, in some cases, both. These aspects include current operating range (>100 kA), current rate of rise (> 10^{12} A/sec), switching precision, trigger efficiency, current reversal, and recovery time. Several electrical and optical trigger methods are described. Pseudo-sparks and BLTs have also been tested in different types of gas lasers including copper vapor-, N_2-, and excimer-lasers.

Introduction

This paper reviews the research and development of the pseudo-spark [1-4,7,10] and the back-lighted thyratron (BLT) [8,9,10], which are new thyratron-type switches. The BLT is an optically triggered version of the pseudo-spark. These switches operate with a low-pressure glow discharge, *not an arc*, and achieve high stand-off voltage by operating on the left branch of the Paschen curve, analogous to a high power hydrogen thyratron. They are typically comprised of two parallel-plane inverted cup electrodes, each with a central hole. The switches are triggered either by injection of charge carriers or by photoemission. A distinction is made between the electrically triggered pseudo-spark switch, which, following the original authors [2] is referred to as a pseudo-spark, and the optically triggered version of the pseudo-spark, which is referred to as a "back-lighted" thyratron, or BLT [8].

'Improved' thyratrons would have one or more improved characteristics, such as peak current, current rate of rise, stand-off voltage, modularity, repetition rate, lifetime and energy dissipation at high power. In general, it is difficult to characterize such improvements in a simple way because improvement in one area can result in degradation of another. The switches described here, the BLT and the pseudo-spark switch, have demonstrated *simultaneous* improvements in these characteristics, and are thus important candidates for a variety of applications.

Principle of Operation

Figure 1 illustrates the scheme of the discharge geometry. Two parallel plane electrodes with holes on a common axis are separated by an insulator ring at a distance d (d typically some mm). With gas pressures of typically 10 Pa, the working range of this geometry is on the lefthand branch of the Paschen curve. At breakdown the longest possible path along d_{eff} is preferred, producing an axial discharge. The applied voltage can be >100 kV with multigap devices. Figure 1 shows the pseudo-spark discharge in a single gap as well as in a multigap pseudo-spark chamber.

Time resolved optical spectroscopy of the pseudo-spark discharge and measurements of delay and jitter lead to the following simple model of the temporal development of breakdown, described in detail in ref. 3. The pseudo-spark starts in the channel according to the generalized TOWNSEND-scheme. As soon as the positive space charge which is caused by this high voltage predischarge reaches a critical value in and around the cathode hole, the discharge extends into the hollow cathode with a velocity of about 10^6 m/sec due to an ionization wave. This leads to a very fast current rise because within the hollow cathode the yield of secondary electrons and the efficiency of electron impact ionization are increased. This fact and the special geometry allow triggering by several methods.

The pseudo-spark triggering methods include a dielectric surface discharge and a pulsed, low current discharge. For the first method an insulated trigger electrode is embedded in the cathode between two dielectric foils of typically 0.1-0.3 mm thickness. The second trigger method is based on a pulsed low-current gas discharge behind the rear cathode surface, which has practically unlimited lifetime (> 10^{10} discharges) and allows repetition rates up to 100 kHz [3]. A third electrical triggering method has been demonstrated using an electron beam injected into the hollow cathode.

The BLT is initiated by photoemission of electrons produced by unfocused ultraviolet radiation from a laser, flashlamp, or other spark source, incident on the interior of the hollow cathode. High power laser initiated switches, such as laser triggered spark gaps, have been under development for over 20 years [5]. The laser triggering mechanism normally requires a focused laser which produces a plasma, electrode damage, and electrode erosion at the laser focus [5]. Photoemission has also been investigated for high pressure spark gap triggering [6], but with little success.

Trigger Methods and Results

Pulsed Low Current D.C. Discharge Trigger

This trigger method was developed by G. Mechtersheimer at ISL, St. Louis, France [4]. An example is shown in Fig. 2. The main switch is separated from the trigger module by a cylindrical cage forming the hollow cathode. This cage screens the trigger section from the main discharge thus providing a practically unlimited lifetime, greater than 10^{10} discharges of the trigger module. The cage is also necessary for the fast current rise.

A positive voltage of up to 300 V applied to the auxiliary electrode influences the hollow cathode of the main switch through holes on the side of the cage. This prevents the build-up of a positive space charge in the hollow cathode and suppresses undesired statistical prefiring of the main switch.

A low current glow discharge ($I_{D.C.}$ < 1 mA) starting from electrode 2 provides preionization inside the trigger section. For triggering, a pulsed gas discharge (maximum current < 1 A) is generated by applying a negative pulse of several kV to the trigger electrode. At the same time the blocking potential is switched to zero, thus enabling the charge carriers penetrating through small holes in the top of the cage to initiate closure. The blocking potential reapplied thereafter accelerates recombination of the switch plasma. Within a few microseconds, depending on the parameters of the preceeding discharge, high-voltage can be reapplied to the switch. The power necessary for triggering the pseudo-spark switch is relatively small, requiring about 200 mW for D.C. preionization and less than 0.2 mJ/pulse for switching the trigger electrode and the auxiliary electrode. The pseudo-spark switch has been shown to work with various gases in a pressure range of 10 - 100 Pa switching positive high voltage as low as some hundreds of volts up to several tens of kV. Anode triggering is also possible, although over smaller ranges of pressures and voltages.

The delay between the application of the trigger pulse and the onset of voltage breakdown of the main switch is governed by a two-stage process:

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14. ABSTRACT
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(1) The onset of the trigger discharge is characterized by a steep rise of the trigger current and is independent of the high voltage applied to the main switch. The build-up time of the trigger discharge strongly depends on the geometry of the trigger section, the pressure, the preionization current, and the trigger pulse characteristics. The best data are achieved for preionization currents which are characteristic of the transition from a normal to an abnormal glow discharge. Figure 3 shows the delay as a function of the preionization current. The best result was a delay of 150 ns.

(2) From the onset of the trigger discharge there is a delay before the build-up of the positive space charge in the hollow cathode of the pseudo-spark chamber. Normally the main discharge is formed within 10 - 50 ns.

Single channel pseudo-spark switches have been designed for medium voltages and currents of typically less than 20 kV and 10 kA. The switches work at high repetition rates of up to 100 kHz and fast current rise rates of up to $5 \cdot 10^{11}$ A/sec with a jitter of typically 1 ns. These switching capabilities are considerably improved by multichannel pseudo-spark switches with as many as 19 discharge channels linearly arranged on common cathode and anode plates [7]. Triggering is again provided by a pulsed low current gas discharge. The inductance of the completely closed switch is less than 0.5 nH. The current rise rate, limited by the resistive breakdown time, is increased to $2.4 \cdot 10^{12}$ A/sec at a voltage of 10 kV.

Surface Discharge Trigger

Preliminary studies were done at CERN, Geneva and the results first described in Ref. [3]. The surface discharge trigger is integrated into the hollow cathode of the main switch by embedding a trigger electrode between two thin insulator discs.(11) A high voltage pulse ($U_{pulse} = 3$ kV, $t_{Rise} < 10$ ns) is applied to this electrode (see Fig. 4). The insulating discs in these investigations were organic materials like Mylar and Capton (both manufactured by DuPont, USA), which lose their surface dielectric strength through treatment with long term high voltage pulses because of a burned-in low-impedance trace of carbon ("conditioning"). If long term pulses are used for triggering the trace of carbon is reproduced, and lifetimes of 10^8 discharges and more can be reached. Later on, however, delay and jitter degrade as a result of the continuous erosion of the insulator. Using short trigger pulse lengths of less than 100 ns, the lifetime of the surface discharge trigger is limited to 10^5 discharges because of the reduction of the carbon trace. Subsequently, the trigger must be 'conditioned' again.

This trigger mechanism results in a short delay between the trigger and the pseudo-spark discharge, as well as very small jitter. Typical values are 30 ns and 0.8 ns, respectively. These values are independent of the power of the spark, in contrast to triggered vacuum gaps. The pulse energy sufficient for fast triggering is below 0.4 mJ.

The following results were measured at switch voltages(11) smaller than 20 kV and currents up to 4 kA. The location of the trigger discharge inside the hollow cathode could be set at four different positions: 1, 3, 5, 7 mm, referred to the cathode surface facing the anode. Figure 5 demonstrates the dependence of delay and jitter on the normalized pressure p/p(Br), where p(Br) is the pressure for self-breakdown at a given voltage in hydrogen. The trigger position was fixed at 3 mm for this figure. The delay increases with decreasing pressure, as well as for decreasing gap voltages. The jitter, on the other hand, is nearly constant in the normalized pressure interval of p/p(Br) = 0.55 to 0.95. Below this it grows rapidly, however. With growing electrode spacing the delay increases as well, while the jitter stays almost constant. The qualitative behavior of these functions is independent of the working gas: in nitrogen the delay is approximately 15% smaller than in hydrogen, whereas the jitter is nearly identical. If the distance from the trigger discharge to the cathode surface is increased, a rise in delay and jitter is observed. Between 1 and 3 mm distance delay and jitter change only slightly, whereas at 5 mm and more a rapid increase is found. This is an important result, because the lifetime of the carbon trace in the 1 and 3 mm positions is significantly different: 40,000 and 150,000 discharges, respectively.

The pseudo-spark can be triggered at the cathode and at the anode. The delay at the anode is longer by a factor 4. In summary, the basic advantages of the surface discharge trigger are its short delay and small jitter. It is a simple construction, needs no power in standby mode, and also requires no additional blocking and control electrodes with corresponding circuitry. Its main disadvantages are reduced lifetime, the production of carbon and gaseous products, and the presence of organic material. These problems may be solved by suitable trigger insulators.

The current rise rate of the switch as a function of working pressure, high voltage and electrode spacing shows a dependency which is typical for low-pressure devices. There is a distinct difference between triggering at the cathode and at the anode. This is illustrated in Fig. 6. When triggered at the cathode the current rise rate was restricted to $3.5 \cdot 10^{11}$ A/sec by the experimental set-up.

Optical Trigger

The BLT is similar to the pseudo-spark [8], but differs in that the conductive phase is initiated by light. The light is incident on the back of the cathode. Typical operating parameters are 10-50 Pa H_2 or He, 3 mm electrode separation, and a few millijoules of ultraviolet radiation. Over 35 kV stand off and 10 kA peak current have been obtained, with circuit-limited dI/dt ~ $4 \cdot 10^{11}$ A/sec. Optical triggering has been demonstrated by 1) using an unfocused laser (Xe Cl @ 308 nm and KrCl @ 222nm) directly incident on the back of the cathode, 2) a flashlamp [9], 3) radiation from a spark generated in air, and 4) by coupling laser radiation into the BLT cathode area through an optical fiber [10].

The unfocused light initiates the discharge through photoemission, rather than through the formation of a plasma at the surface of the cathode. This is ordinarily not possible with a high current switch, as it has not been possible to fabricate devices that have both photosensitive cathodes and have the cathode in a region where either the laser or arcing produce permanent cathode damage. Although circuit limited, the compact structure of the anode and cathode as well as the pseudo-spark and BLT results suggest that extremely high dI/dt should be possible. A two-gap construction achieved stand-off voltages in excess of 60 kV. It should be straightforward to connect several BLTs in parallel in order to lower the inductance and increase peak current capability. Because several switches can be triggered by the same laser, pulse-to-pulse jitter should be minimal.

Flashlamp Trigger

Characterization of the laser triggered switch revealed that only a few millijoules of light energy was required to initiate the discharge, prompting the design of a switch using a UV flashlamp. This version has significantly improved power gain and is a simpler device. The flashlamp-switched BLT has operated at hold-off voltages >37 kV, peak currents of more than 10 kA in 2 µsec pulses, and at a repetition rate of 100 Hz. This repetition rate was limited by available power supplies and not the switch. The power gain, measured as the ratio of switched energy to trigger energy, was ~1400. High repetition rates should be achievable, partially because energy loading restrictions will be somewhat relaxed as a result of the simpler structure. A UV flashbulb (EG&G FX265) was used as the trigger light source. The bulb has an electrical to light energy conversion of about 14% with up to 39% of the light energy below 300 nm wavelength. It is mounted directly behind the hollow cathode such that the window of the bulb is also the window of the switch allowing the maximum coupling of light into the hollow cathode. With an improved trigger and discharge circuit for the flashlamp, the risetime of the light pulse was reduced to 35 ns, resulting in delay and jitter of typically 260 and 11 ns, respectively [10].

Fiber Optic Trigger

It is also possible to use a fiber optic waveguide to deliver a UV light pulse to the cathode . Advantages of using an external light source for triggering include complete electrical isolation, serviceabilty of the trigger separate from the switch, and ease of

triggering multiple gaps/switches simultaneously. At a wavelength of 308 nm (XeCl excimer laser), consistent triggering was found with as little as 1.5 mJ of laser energy incident in a 15 ns pulse on the cathode. The pressure was 15-26 Pa of H_2 and the switch was operated at a repetition rate of 1 to 10 Hz at voltage up to 25 kV and a pulse duration of 1.5 µs. The circuit was not designed to test the switch for high peak currents and dI/dt's, and consequently these numbers are rather modest.

The best jitter and delay times to date are 0.8 ns FWHM and 78 ns, respectively, operating at a pressure of 27 Pa of H_2, 10 kV anode charging voltage, 4.4 mJ /308 nm light from the fiber, and molybdenum electrodes. A serious concern for this device is the metalization of the glass walls adjacent to the electrodes and of the fiber due to evaporation of the electrode material around the holes. We have operated the switch at 15 kV (50 Joules/pulse) for $1 \cdot 10^5$ shots with nickel electrodes and over $2 \cdot 10^5$ shots with molybdenum electrodes. At the end of these runs, the switch often flashed over at the metalized glass surface near the electrodes and the output power from the fiber had significantly decreased.

The number of photoelectrons generated by the UV light pulse from the fiber has been directly measured using a collection electrode within the hollow cathode. From $5 \cdot 10^8$ to $2 \cdot 10^9$ photoelectrons were measured for light pulse energies ranging from 1.5 to 6 mJ at 308 nm. This corresponds to a quantum efficiency of about 10^{-7}, which is expected since the work function of the electrodes (about 4.25 eV for molybdenum and 5 eV for nickel) is slightly greater than the energy per photon (4.025 eV at 308 nm). Comparable results were achieved using only 10 µJ of laser light at 222 nm incident on the rear cathode surface. The corresponding quantum efficiency is almost a factor of 700 larger than that at 308 nm.

Applications

Prototypes have been tested in different types of gas lasers which are normally driven by hydrogen thyratrons or high pressure spark gaps. A pulsed discharge triggered pseudo-spark replaced a hydrogen thyratron in discharge heated longitudinal copper vapor lasers [4]. At switched voltages between 9 and 15 kV, peak currents of 400 - 1,500 A at pulse widths of 60 - 100 ns have been achieved at repetition rates up to 30 kHz.

A pseudo-spark triggered by a surface discharge was used as a switch for a TEA-N_2-laser [11]. The current risetime of 16 ns was primarily determined by the discharge circuit. At a voltage of 15 kV and a maximum current of 8 kA the shortest switch turn-on delay amounts to 30 ns, including the delay of the electronic control device. The overall jitter of the laser is less than 1.3 ns at a minimal laser delay of 63 ns. A current reversal of 100% can be tolerated without damage. This method of triggering requires a small, very fast and reliable control device. For this purpose a seven stage marx type pulse generator, which consisted of selected avalanche transistors, was developed [12].

A flashlamp-triggered BLT was tested as a replacement for a thyratron in a commercially available XeCl excimer laser. The magnetic "assists" in the pulse circuit were removed and the laser performed at least as well as with the thyratron and magnetic circuitry.

Four pseudo-sparks in parallel have been used at CERN to operate a prototype plasma lens [13]. A total of over 400 kA has been switched, e.g. over 100 kA per switch. These switches operate at 16 kV, 1 to 10 Pa He, 5 microsecond pulse length, and have a dI/dt of $1.5 \cdot 10^{11}$ A/sec at a repetition rate of 0.4 Hz. These pseudo-sparks have switched 3.5 kJ/shot for over 400,000 shots. The amount of charge transferred per shot is greater than 0.4 Coulombs. These pseudo-sparks are capable of 100% current reversal.

[9] G.F. Kirkman and M.A. Gundersen, to be published.

[10] C. Braun, W. Hartmann, M.A. Gundersen, V. Dominic, G. Kirkman, and G. McDuff, to be published.

Conclusions

Using a pseudo-spark switch triggered by a surface discharge gap it is possible to initiate switching processes with time delays less than 40 ns and a jitter of 1 ns. These results are valid for voltages up to 20 kV and currents of 10 kA. The rate of current rise $dI/dt = 5 \cdot 10^{11}$ A/sec is partly restricted by the discharge circuit. Comparable perfomance has been demonstrated with the BLT, which also has the special feature that it can easily be electrically isolated. The experimental work done up to now demonstrates that these switches can not only perform as well as existing thyratrons, but also possess some of the important advantages of the high pressure spark gap, including high peak current and high rate of current rise. Very high repetition rates and lifetimes can be achieved with the 'charge injection triggering' method. High lifetimes are also expected for the other triggering methods because of the cold cathode operation.

In summary, versions of these switches under varying operating conditions have switched over 100 kA, operate in a glow discharge mode without electrode degradation from arcing, have demonstrated over $2 \cdot 10^{12}$ A/sec dI/dt, and sub-nanosecond jitter, using a cold cathode.

These switches are the result of basic research programs. The anomalously high cold cathode emission (>>hot cathode) and current densities (40,000 A/cm^2, >>normal thyratron plasmas), obtained in a non-arcing mode and with a simple structure, strongly encourage further basic study of plasma devices. The physics of the cathode emission and high current density require study, and further device applications should be sought.

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References

[1] M.A. Gundersen, R. DeWitt, A.K. Hyder, C.R. Jones, J.A. Kunc, M.J. Kushner, E.P. Muntz, G. Schaefer, and P.F. Williams, "Research issues in power conditioning," in Proceedings of the Seventeenth Power Modulator Symposium, Seattle, Washington, June 1986.

[2] J. Christiansen, C. Schultheiss, "Production of high current particle beams by low pressure spark discharges," Z. Phys. A290, 35, 1979.

[3] D. Bloess, I Kamber, H. Riege, G. Bittner, V. Brueckner, J. Christiansen, K. Frank, W. Hartmann, N. Lieser, C. Schultheiss, R. Seeboeck, W. Steudtner, "The triggered pseudo-spark chamber as a fast switch and as a high-intensity beam source," Nucl. Instrum. Meth. 205, 173, 1983.

[4] G. Mechtersheimer, R. Kohler, T. Lasser, R. Meyer, "High repetition rate, fast pseudo-spark switch," J. Phys. E: Sci. Instrum. 19, 466, 1986.

[5] A.H. Guenther, J.R. Bettis, "A review of laser triggered switching," in Proceedings of the IEEE 59, 689, 1971, and references therein.

[6] K. Harsch, H. Salzmann, H. Strohwald, "UV laser triggering of spark gaps by two-quantum photoelectric effect," Phys. Lett. 55A, 153, 1975.

[7] G. Mechtersheimer et al., J. Phys. E: Sci. Instrum., to be published.

[8] G.F. Kirkman and M.A. Gundersen, "A low pressure, light initiated, glow discharge switch for high power applications,' Appl. Phys. Lett. 49, 494, 1986.

[11] K. Frank, E. Boggasch, J. Christiansen, A. Goertler, W. Hartmann, C. Kozlik, "High repetition rate pseudo-spark switches for laser applications," presented at the SPIE Conference, Los Angeles, CA, January 1986.

[12] J. Christiansen, K. Frank, W. Hartmann, "A fast, solid state high voltage pulse generator," Nucl. Instr. Meth., accepted for publication.

[13] E. Boggasch, V. Brueckner, H. Riege, in Proceedings of the 5th Pulsed Power Conference, Arlington, VA, pp. 820, 1985.

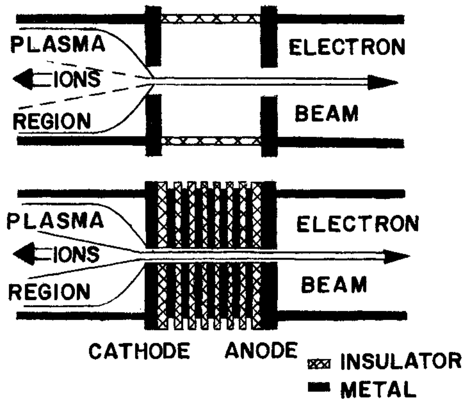

Fig. 1 Schematic of single-gap (top) and multi-gap (bottom) pseudo-spark chambers, showing the discharge geometry.

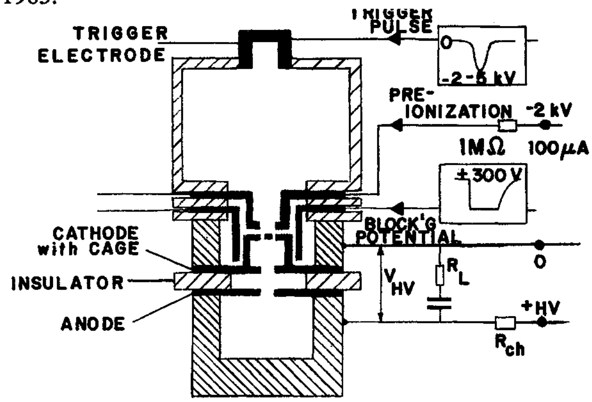

Fig. 2 Experimental pseudo-spark switch design for pulsed-glow-discharge triggering, and electrical circuit.

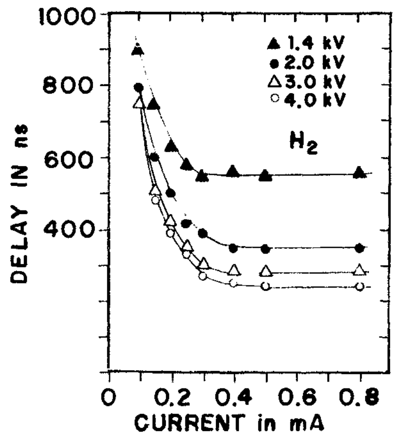

Fig. 3 Delay of the pulsed-glow-discharge triggered pseudo-spark as a function of the preionization current, for different trigger pulse amplitudes.

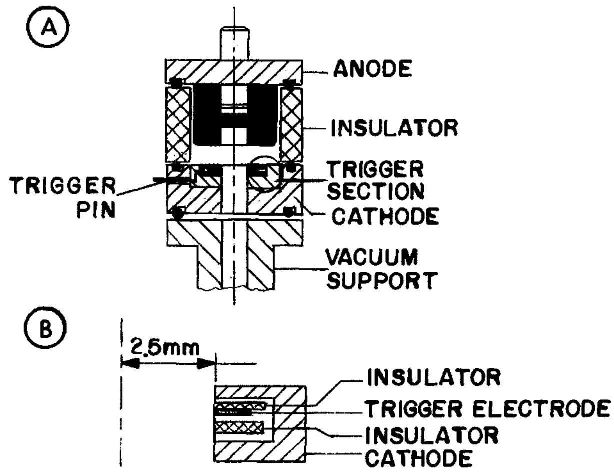

Fig. 4 Schematic of the slide-spark triggered pseudo-spark switch (a), and enlargement of the trigger section (b).

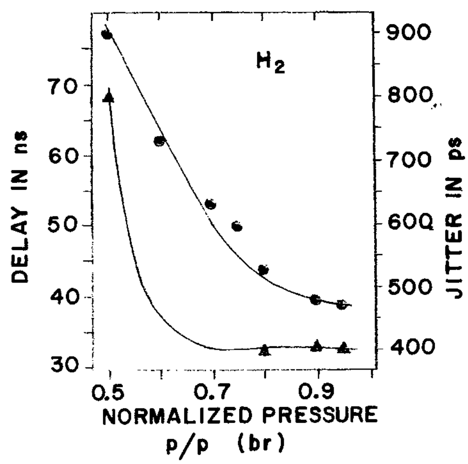

Fig. 5 Delay and jitter of the slide-spark triggered pseudo-spark as a function of the normalized pressure p/p(br), where p(br) is the pressure for self-breakdown at 10 kV.

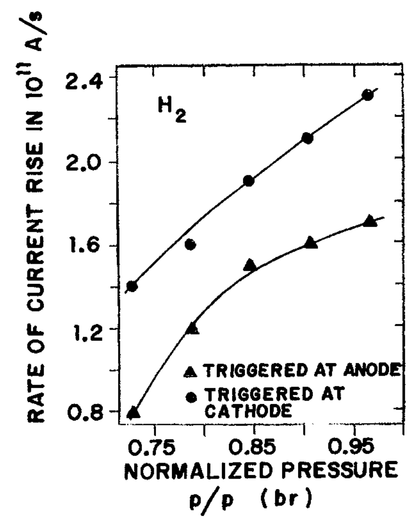

Fig. 6 Rate of current rise as a function of p/p(br) in hydrogen at 10 kV for anode and cathode side triggering, respectively.